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DESIGN OF A HIGH CAPACITY LONG RANGE CARGO AIRCRAFT

PURDUE UNIVERSITY

FINAL REPORT
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FINAL REPORT

THE DESIGN OF A HIGH CAPACITY LONG RANGE CARGO AIRCRAFT

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SUMMARY

This report examines the design of a long range cargo transport to attempt to reduce ton-mile shipping costs and to stimulate the air cargo market. This design effort involves the usual issues but must also include consideration of: airport terminal facilities; cargo loading and unloading; and, defeating the "square-cube" law to design large structures. This report will review the long range transport design problem and several solutions developed by senior student design teams at Purdue University. The results show that it will be difficult to build large transports unless the infrastructure is changed and unless the basic form of the airplane changes so that aerodynamic and structural efficiencies are employed.

Introduction

The objective of the senior design class project for the School of Aeronautics and Astronautics at Purdue University was to provide a conceptual design for a high capacity (>250,000 lb. payload) cargo aircraft with a range between 5000 and 8000 nmi. to compete with the current Boeing 747-400 F freighter and to reduce the cost of air freight dramatically. Where possible, this design was to consider incorporating prudent amounts of advanced technology and new configuration concepts. Forecast production go ahead is 1998 with the first certificated aircraft delivered in 2001.

This report reviews project objectives and constraints, and summarizes some of the solutions developed by student design teams at Purdue University during the semester-long senior design course. It begins with a discussion of the market needs and constraints and then summarizes different approaches taken to solve the problem. Finally, some "lessons learned" are discussed.

Design Resources and Organization

Teams were composed of 5 to 6 members, each with a primary responsibility. The design course at Purdue is one semester long. This allows about ten weeks of group effort to produce a preliminary design after all the basic areas of effort are reviewed. In addition to the emphasis on technical effort, the requirements for communication in terms of writing quality and oral presentations are stressed.

The Request for Proposal

The project itself was suggested by Morris and Sawyer[1] of NASA/Langley who suggested that economic gains might be realized if the cost per ton-nautical mile could be reduced to the levels of intercontinental, water-borne shipping. Our approach was to try to reduce costs to a level approximately one-half the current costs of the 747-400-F and to take advantage of the economies of scale in hauling large amounts of air cargo.

The still air range and cargo capacity were chosen by the individual design teams on the basis of the perceived market and competition. The requirements were as follows.

Fuel reserves equal to 5% of primary trip fuel must be included in the mission. Cruise speed is important. The use of advanced materials is highly encouraged, consistent with safety, maintainability and cost requirements. Emphasis is placed on minimal empty weight and cost.

The use of efficient, maintainable engines is encouraged, consistent with cost and development considerations. It is strongly recommended that upgrades or modifications of existing engines be considered.

The use of advanced airfoils and innovative concepts is strongly encouraged, consistent with customer acceptance and performance. The design of the fuselage must show evidence of concern for cargo loading and unloading.

Cost and Maintainability

Acquisition and operating costs are major factors in evaluating the suitability of the design. These costs must be determined using generally accepted data and estimation procedures. The design must clearly show that maintenance and reliability have been considered.

Data requirements

The technical proposal must be specific and complete, but must be less than 100 pages, excluding the Appendix. This proposal must demonstrate a thorough understanding of the requirements and opportunities for the design RFP. (The class developed a suggested Table of Contents for this report during the semester.)

Critical technical issues and problem areas must be clearly identified in the proposal and adequately addressed. Descriptions, sketches, drawings and analysis, method of approach and discussions of new techniques should be presented in sufficient detail to permit accurate engineering evaluation of the proposal.

Trade-off studies must be included in the proposal to describe the process of arriving at the final design. A history of the design development, including possible

designs that were rejected and their reasons for rejections, must be included.

Basis of Judging Team Design Results

Responses to this proposal were be judged in four primary categories.

Technical Content The correctness of theory, validity of reasoning, apparent understanding and grasp of the problem.

Organization and Technical Presentation The ability to present a description of the design and to clearly communicate its advantages is an essential factor in evaluation. Organization of the design report, clarity and skillful inclusion of pertinent data are major factors in this evaluation.

Originality The design proposal should show that there was independence of thinking or a fresh approach to the problem. Does the method and treatment of the solution show imagination or extend previous efforts or is it simply a rehash of an existing solution? Evidence of team effort and participation are essential.

Practical Application and Feasibility The proposal should present conclusions and recommendations that are practical and feasible and not merely lead the evaluators into other unsolvable problems. Has the team made mention of shortcomings and made recommendations for further improvement if time permitted?

Large Cargo Aircraft Design - the Market

The design of a large cargo aircraft poses unique problems. Design addresses a customer need and then proposes a solution that meets the requirements while addressing the constraints imposed on the product.. The consideration of need requires an answer to the question "Where is the market for large capacity, long range cargo aircraft?"

In terms of total market share, air cargo makes up only a small fraction of the total demand for freight traffic in the United States. (1% or less by weight). In terms of the standard measurement unit of ton-miles, every year in the United States there are about 2.5 trillion ton-miles of cargo activity. The largest freight carriers consist of: rail, pipelines, barges and trucking. The air freight business is a distant fifth place in terms of tons of cargo carried. Total world air freight volume is only about 50 billion revenue ton-miles.

On the other hand, world air freight activity is growing at a rate between 5 and 9 per cent each year in some markets. The types of markets that are dominated by air freight carriers are interesting. Within the U.S. the package freight business is very active. Overnight letters, second-day letters and courier boxes are carried on passenger aircraft and by dedicated aircraft such as those operated by Federal Express.

Major air freight shippers have contracts with companies such as Land's End and Xerox to ship merchandise and spare parts from one part of the country to the other at reduced rates. Other companies such as IBM provide contracts to maintain stocks of merchandise and spare parts in selected locations around the country. This type of activity is a major portion of U.S. air cargo, but provides a smaller percentage of world cargo activity because of the necessity of taking air cargo through customs at international borders.

In the international market, there are some unusual, but low volume types of cargo that are shipped by air. These include items such as ship propellers for stranded tankers, generators for Britain during electric utilities strikes, sandbags (empty) for Midwest floods and insecticides for African locust plagues. This type of cargo is usually shipped on older airplanes whose operating cost is low and which can afford to operate relatively few hours each year.

More common types of merchandise that move via air cargo include merchandise that is warehoused overseas. Items such as unusual size tires, for construction equipment or race cars suits with unusual sizes or specialty shoes are some examples. In addition, auto parts and fashion merchandise are often warehoused overseas and then sent to this country on demand.

Air freight helps business because the cost of air freight shipment is more than offset by savings in reduced local inventory and eliminating rental of small warehouses, as well as reducing or eliminating costs of maintaining a staff at remote sites. As a result, one plans not to have an item in stock locally, but then relies on air transport, for instance, from Japan to the U.S.

A different type of important air cargo is perishable cargo. This includes fish caught in New England and shipped to Japan and flowers grown in South America and shipped to the U.S. Reliability is a must for this type of cargo because it is "time sensitive."

Air cargo also includes high value items such as furs, computers, expensive clothing and even money itself. Canceled checks are moved from one location to another by air freight. In 1988, the U.S. exported 400 million tons of cargo worth about $320,000,000,000. While the exports shipped by air consisted of only 0.4% by weight, they were 29% by value.[1] The savings in funds tied up for a small time more than pays for the air cargo fees. In addition, the possibility of theft is reduced by shipping by air because the warehouse time is reduced, thus reducing exposure to pilferage.

Items needed in or from inaccessible locations also present an opportunity for air cargo. This includes mining machinery for the upper Amazon, oil drilling rigs to Siberia and road building machinery to remote areas of China. A different category is livestock for breeding overseas, Airbus fuselages or rocket booster tanks. While this mission is important, it does not represent a high volume of cargo requiring a large fleet of aircraft.

There are many problems generating revenue in the air cargo business. Revenue depends largely on weight of items. transported. The density of air cargo varies widely. If the density is low, there is so limited volume on board so that the aircraft may fill with cargo, but still not have

anywhere near the payload weight capacity. This is called "cubing out before it weighs out."

The problem of pilferage, while reduced in some cases compared to regular shipping, is increased in other areas because of the size of items shipped by air cargo. Seasonality also poses a problem because some goods such as vegetables are only grown at certain times of the year.

The problem of "back hauling" poses another difficulty for air carriers. The aircraft may fly into a location fully loaded, but there may be no revenue cargo waiting to be hauled back.. Returning with the aircraft empty or with only a small load drives costs upward because of reduced utilization.

Problems of clearing customs have already been mentioned, but deserve mention again. Sealed containers can solve this problem to some extent, but the number of items and the type of items creates difficulties because duties imposed and inspections may cause delays.

Containers play an important role in air cargo shipments. Since the cargo shipped by air is time sensitive, using containers can reduce ground time or even reduce the need for warehouse space at the airport itself. The largest containers are the 8 ft. by 8 ft. by 10 ft./20 ft./40 ft. variety. It is interesting to note that the 8 ft. by 8 ft. container cross-section traces its origins to the Medieval requirement of letting a wagon pass through the fortified gate of walled cities.

Other containers such as standard LD-3's will fit into the bellies of 747, A-300 and 777 passenger jets (but not 767's). Despite their utility, containers have problems of cost, added weight, theft and the need for return. (Containers make excellent woodsheds and outbuildings in some Third World countries.)

Sharing airports with passenger traffic is another problem in the air cargo industry. Space at commercial airports is expensive and can also drive costs up. Freighters are often looked upon as simply adding to airport congestion. Cargo terminals are often remote and there are security problems around the airport because of the large numbers of trucks coming into the airport. Cargo handing equipment must be provided. Roadways must be built to handle traffic. A large amount of air cargo moves at night. Noise restrictions can eliminate some markets or increase the expense.

Military air transport provides an additional market for large cargo aircraft and a potential source of aircraft for commercial operators. The military needs heavy, long range lifting capability. One Army division requires 50,000 tons of cargo, 50,000 tons of fuel and 10,000 people. It also requires oversize and outsize capability, self-sufficiency, self-loading and unloading and refueling in the air.

Military cargo aircraft must have the capability of landing on very rough airfields. and have high reliability, air drop capability and must load troops with their equipment. Military freighters cost a lot of money because of the above capabilities. It is difficult to "cheapen" military freighters such as the C-5 for commercial use.

Previous studies

The air cargo industry is a growth industry. Long term growth rates are forecast to be about 2 percentage points more than commercial passenger growth because air cargo transportation relies on international trade flows that are strongly dependent on world-wide economic growth. This trend will happen "only if the transport system from shipper to final destination offers a viable and efficient alternative to surface transport."[2]

Previous NASA studies from the 1970's have concluded that there is a latent demand for air cargo shipping that might be stimulated if air cargo costs could be reduced drastically.[3,4,5] This market is currently dominated by competition between dedicated freighters and current wide-body passenger transports.

These studies also concluded that aircraft larger than the 747 (now the 747-400-F) would have economic problems because of their low production rates and Return of Investment (ROI). There are also problems of the infrastructure handling larger airplanes, including simple problems of airport runway overpasses being strong enough to withstand loads imposed by larger airplanes.

The real competition for intercontinental cargo is the containerized shipping vessel.[1]. A large container ship can handle 4000 containers with an 8'x8'x20' size. The price of this ship is about $130,000,000 (about the same price as a new 747). Shipping costs for this type of conveyance range from 3.6 cents to 9.2 cents per ton-nmi. Studies have also indicated that the value of money lost because of finance charges required for slow movement of cargo container shipment is about 3 cents per ton-nmi.[1]

The Boeing 747-400-F can carry 29 8'x8'x10' containers with a payload capacity of 280,000 lb. for ranges of about 5000 nmi. Payload and range depends on the payload weight This aircraft is very efficient, but was designed first and foremost for the passenger market and then converted for cargo use.

The key to the success of any cargo aircraft development is the stimulation of air cargo demand to exceed that currently projected. The key markets are intercontinental. With this in mind, we set our goals to be reducing the direct operating cost (DOC) of the new aircraft to less than 1/2 of the 747-F (currently between 35 and 50 cents per ton-nmi.)while maintaining or exceeding its range. We also projected that if we did this we might stimulate demand so that 300-400 aircraft might be built.

There is a need to replace an aging fleet of first generation jets, to develop better air cargo networks, and the need for a fleet of pure cargo aircraft with different loading capacities and range capabilities. The overall fleet of medium and long haul cargo jets is forecast to grow from 826 aircraft in 1991 to 1437 aircraft in 2005. Airbus Industrie forecasts the need for about 220 aircraft with cargo capacity exceeding 80 metric tons.[2]

Special Design Issues for Large Aircraft

To reach over-the-water markets, we require a long range aircraft with a large payload capacity and a small ratio of operating empty weight to take-off gross weight (TOGW). The cruise portion of the flight dominates the mission of the long range transport. Estimating the fuel required for a cruise dominated mission with the Breguet range equation illustrates fuel requirements. This estimate reads:

$$W_{fuel} \cong W_{TO}\left(1-e^{\frac{-Rc_j}{Ma^{L}/_{D}}}\right) \qquad (1)$$

where R=range, c_j= thrust specific fuel consumption, M=cruise Mach number, a=speed of sound at cruise altitude and L/D is the estimated value of cruise lift to drag ratio.

Equation 1 shows that the fuel required for the mission approaches the TOGW as range R increases. It is not unusual for the fuel fraction (ratio of fuel weight to take-off gross weight) to be of the order of 0.45, even if the aerodynamic efficiency (ML/D) is high and the engine TSFC c_j is low.

For preliminary estimates of the TOGW, we can use the relationship of the form

$$W_{TO} \cong \frac{W_{payload}}{1-\overline{m}_{fuel}-\overline{m}_{empty}} \qquad (2)$$

where $\overline{m}_{fuel}$ is the fuel fraction $^{W_{fuel}}/_{W_{TO}}$ and $\overline{m}_{empty}$ is the empty weight fraction. The empty weight fraction becomes slightly smaller as TOGW increases.[6] This occurs because the dimensions and size of the megatransport allow for more efficient use of high strength materials in the structure and more dramatic weight savings if advanced composite materials are used.

Increased aerodynamic efficiencies may also occur because parasite drag may be reduced due to the larger Reynolds numbers at which large aircraft operate. The coefficient of friction C_f decreases because of an increase in Reynolds Number. Assuming turbulent flow over the entire wing, the C_f is approximated by[6]

$$C_f = \frac{0.455}{(\log \mathrm{Re})^{2.58}(1+0.144M^2)^{0.65}} \qquad (3)$$

where M is the Mach number and Re is the Reynolds number. Aircraft with larger characteristic lengths (wing chord, fuselage length, etc.) will have smaller friction coefficients, all other things being equal. Even with these potential advantages, the TOGW quickly grows as the range increases.

Balancing these problems, operating costs, especially fuel cost per ton-mile, decreases as payload weight increases. There will be a minimum fuel cost for a given payload weight and a given range. This minimum fuel cost reflects the economies of scale for any given design.

The large size of a transport with cargo capability exceeding the B-747-400-F places demands on technology, including structures, manufacturing, landing gear and passenger configuration, to name a few items. These issues for the design of large transports are discussed in a variety of recent articles.[7,8]

Airports

Constraints arise if existing facilities are to be serviced. These include service to terminals built to accommodate wingspans less than 220-240 feet and fuselage lengths of the order of 220 feet. This constrains the span of the cargo transport wings and makes drag reduction difficult. Another serious problem is the logistics of quickly loading or unloading large amounts of cargo.[9]

Structural Design

Among the issues faced by the structural designer of large transports is the so-called "square-cube law." The square cube law is a statement regarding the relationship between the loads, which are assumed to be proportional to weight, and the stresses in the structure. For similar structures of different scales, the load increases as the cube of linear dimensions and the cross-sectional areas increases as the square of the linear dimension.[10]

If the size of the object is doubled (for instance, we simply scale up an existing design) then the stresses double. Therefore for a given material with a given ultimate stress, the square-cube law limits the size of the object. As a result, we can not simply make the aircraft larger, we have to make it different. This will be illustrated when the student designs are discussed later.

Recent aircraft design has focused on using new materials and structural design techniques. New materials , such as aluminum-lithium, and advanced composite materials have allowed changes in structural design. This "defeats" or at least holds off the detrimental effects of the square-cube law and allows larger aircraft to be built. Finally, the weight of some items on an aircraft are not functions of scale.

Fuselage design

Containment of cargo on a large transport requires an examination of how to keep the wetted area per unit volume small and how to arrange large cargo containers. Fuselage design is challenging because of aircraft maximum length constraints imposed by terminal facilities and the requirements for aerodynamic efficiency of the fuselage shape. This latter feature is usually at odds with cargo handling requirements because short, stubby fuselages are aerodynamically inefficient.

Wing Design

Wing design is driven by size constraints, imposed by existing aircraft terminal facilities, that limit the wing span of the aircraft. Consequently, it becomes important to consider the trades involved in wing design with the size constraint on the wing span.

The most important factor in controlling the induced drag is the wing span loading (the ratio of aircraft weight to wing span). With the span limited and the weight requirements high, one must look to new configurations. The wingspan constraint was addressed by using folding wing tips and multiple lifting surfaces, including tandem wings, canard configurations and three surface configurations.

Another key parameter in wing design is the choice of wing area. The cruise lift coefficient C_L is related to aircraft weight W and wing planform area S as follows

$$C_L = \frac{W/S}{q} \qquad (4)$$

where q is the dynamic pressure. From a structural point of view the wing area should be small to decrease wing weight and empty weight. As W/S increases with decreasing wing area, C_L increases. This results in an increase of induced drag, which depends on the square of C_L as follows

$$C_{Di} = \frac{C_L^2}{\pi e AR} \qquad (5)$$

where AR is the aspect ratio and e is Oswald's efficiency factor. As a result of increased induced drag, more fuel is required, so that the take-off gross weight increases even though wing weight decreases. The matter is further complicated by changes in the parasite drag as wing weight changes. Clearly there is an optimum trade-off between wing area, induced drag and fuel required.

This trade between wing area, weight, drag, and take-off gross weight exists for every type of aircraft. However, this trade is very evident in the large cargo transport because of the large wing areas involved and the large take-off gross weights.

Engines

Large transports must have efficient propulsion units. These engines must meet thrust requirements, noise standards and emission standards. Most teams designed engines with relatively low TSFC's (between 0.4 and 0.5 lb/lb/hr) at cruise.

Although there are some large engines that may meet the requirements for large transport propulsion, the engines used on the Purdue designs were designed to meet the special requirements of their airplane. The cycle analysis programs ONX and OFFX, developed by Mattingly and Heiser,[11] were used for engine design and performance predictions.

Large engines create design problems over and above the usual problems of finding an efficient design cycle. The large intakes require severe restrictions on ground clearance. This leaves the designer with a choice of lengthening the landing gear, adopting a high wing design or mounting the engines on top of the wing.

In addition to these problems, FAR 36 and ICAO Annex 16 (Chapter 3) have restrictions on lateral, take-off and approach noise.[12] While these regulations permit increased noise with increased aircraft weight, the upper level of noise generation is fixed for aircraft weights greater than 900,000 pounds.

Cost and Price Estimation

The large cargo transport must have low operating expenses compared to existing aircraft such as the B-747-400-F aircraft. These operating expenses translate into direct operating cost (DOC) per block hour of operation and direct operating costs per available seat mile.

The acquisition costs were estimated using methods described by Roskam.[13] Direct operating costs (DOC) were estimated using a model suggested by the Association of European Airlines. The direct operating costs and the cash flow analysis required to set the manufacturers selling price were calculated, using a computer model supplied by Professor J.W. Drake[14] The input to the DOC model includes mission block time, fuel requirements, cost data for labor rates, fuel prices, engine prices, aircraft purchase price, maximum weight, stage length, payload and number of crew members.

A Summary of Team Final Configurations

This section will present five 1993-94 team design efforts. These designs illustrate the range of solutions developed because each of these designs represents a different path taken by students. The reader should keep in mind that the final results at the end of the semester are preliminary level. At the close of a semester the students are finally aware of the trades and are aware of where they need more effort. On the other hand, for the most part, these efforts indicate a remarkable level of understanding and effort.

To place these student designs in perspective we have listed, in Table 1, the existing aircraft that these Purdue design will compete with.

Table 1 - Large transport competitors

Aircraft	TOGW (lbs)	payload weight (lb)	Range (nmi)
747-400F	873,000	244,000	4950
C-5A Galaxy	800,000	264,700	N/A
Antonov 124	>1,000,000	330,700	2800
Antonov 225	1,323,000	551,000	N/A

The KOTS Condor (C-6)

The design of the C-6 Condor was selected and refined by its design team to be an efficient, unconventional answer to problems and constraints posed by the RFP. This design, whose planview is shown in Figure 1, has an estimated empty weight of 624,000 lb. but has a take-off gross weight of 1,500,000 lb. and is estimated to cost $170,000,000.

The range of the C-6 is 5500 nmi. when carrying a payload of 400,000 lb with a cargo density of 10 lb/ft^3. The inner volume of the fuselage will hold 51 8x8x10' containers and, when fully loaded, is able to transport this cargo at a direct operating cost of 25 cents/ton-nmi.

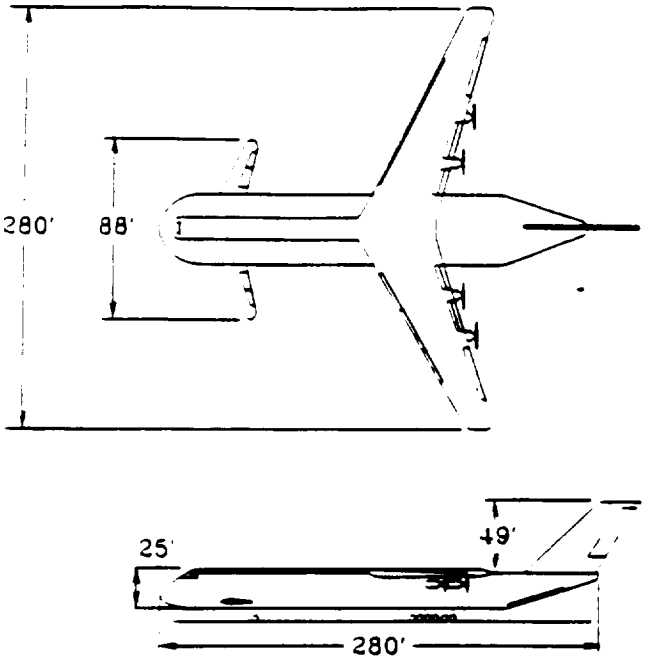

Figure 1 - The KOTS C-6

The cruise speed of the C-6 is 453 knots at an altitude of 37,000 ft. (Mach 0.79). This condition was chosen to reduce wing sweep to reduce wing weight. The aircraft is powered by a contra-rotating prop-fan engine with a TSFC of 0.435 lb/lb/hr.

The aircraft fuselage was designed to hold out-size military cargo such as tanks and helicopters for military supply missions to destinations with improved runways. This military configuration is shown in cross-section in Figure 2.

The C-6 has its best economy at shorter ranges, as shown in Figure 3. This figure shows the estimated differences between the DOC's of the C-6 and the smaller 747-400-F as a function of range.

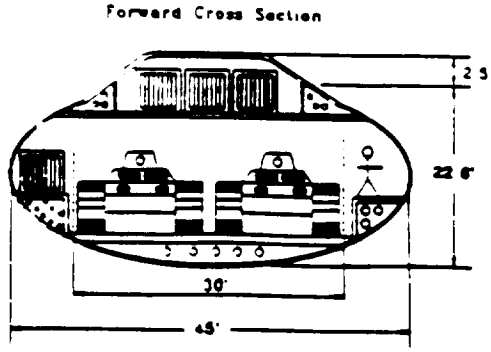

Figure 2 - C-6 fuselage cross-section with military cargo

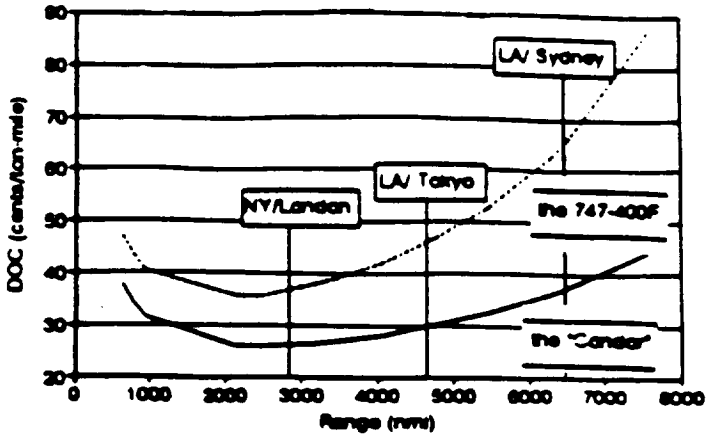

Figure 3 - Comparison of estimated C-6 DOC's cents/ton-nmi) and the 747-400F as a function of range.

The Icarus

The Icarus, shown in Figure 4, is a multiple fuselage transport aircraft. This choice was dictated by the team's desire to have versatility and large payload weight and variety. The aircraft uses the C-wing concept.[14] This configuration promises to preserve relatively large L/D's in cruise and at the same time reduce the required wing span so that current runways may be used.

The range of the Icarus with a payload of 382,000 lb. is 7500 nmi., while the range is 5000 nmi. with 500,000 lb. of cargo. To perform this mission, the aircraft will have a TOGW of 1,490,000 lb. and an operating empty weight (OEW) of 609,000 lb. Cargo loading and unloading was provided by both forward and rear access doors, as shown in Figure 5.

The engines chosen for the Icarus are off-the-shelf GE90 engines originally designed for the Boeing 777 aircraft.. A three engine configuration was chosen to improve reliability and reduce maintenance costs.

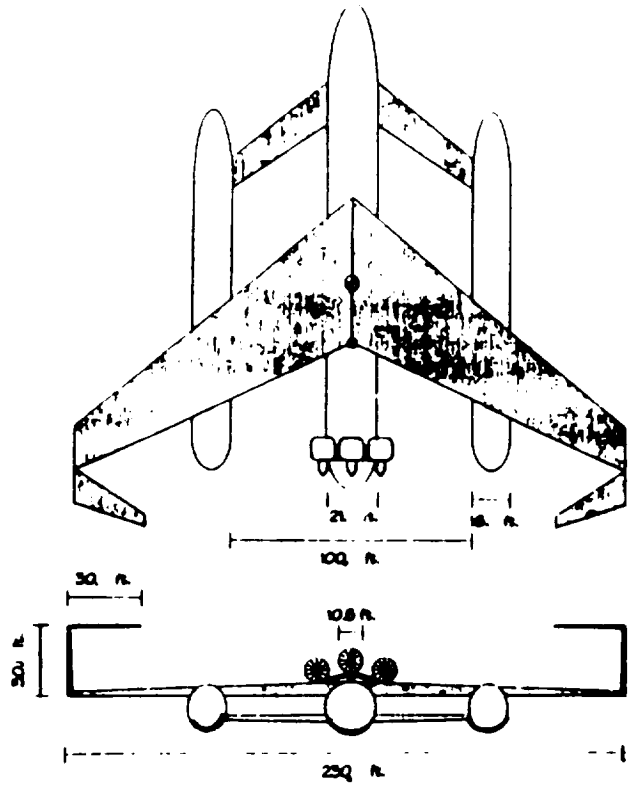

Figure 4 - The Icarus C-Wing design

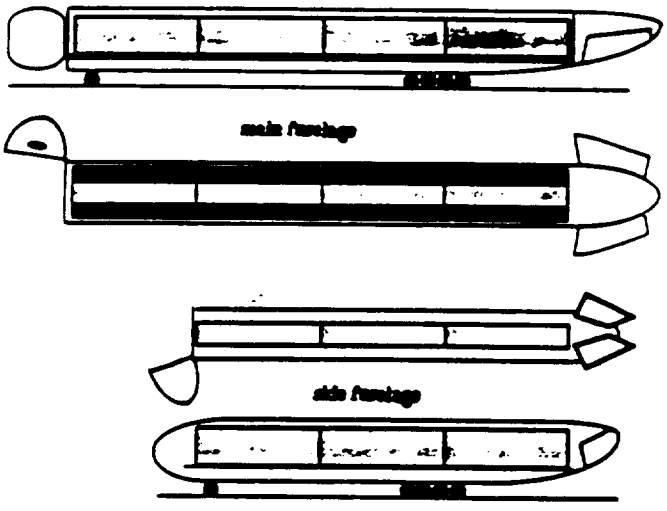

Figure 5 - Icarus cargo loading and unloading doors

The CW1- Pelican

Another design that used the C-Wing concept was the Pelican, shown in Figure 6. This aircraft uses 6 engines with resulting TOGW of 1,680,000 lb. and a range of 6500 nmi. The payload was chosen to be 465,000 lbs.

The cruise begins at 31,000 ft. with a Mach number of 0.75 to retain the advantages of speed , but still reduce wing weight. Because the team estimated that only 180 aircraft would be needed, the estimated price for this aircraft was quite high, about $330,000,000. however, the design team believed that the aircraft's DOC efficiency (22 cents/ton-nmi) would allow the operator to recover these increased acquisition costs in about 14 years.

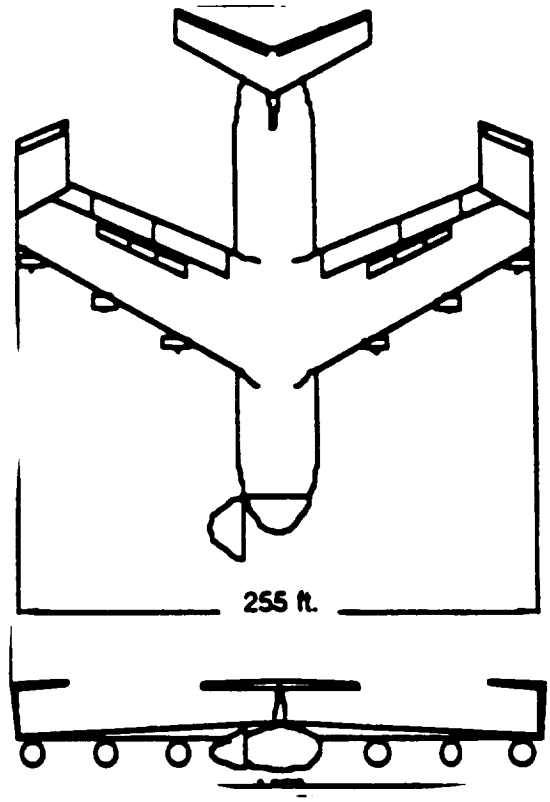

Figure 6 - CW1 - Pelican

The HNZ57 - Super Colossus

The HNZ-57 Super Colossus, shown in Figure 7, is a 1,350,000 lb. aircraft with a payload capacity of 300,000 lb. and a range of 7000 nmi. The cost is estimated to be $170,000,000 with a production run of 200 aircraft. The DOC for this aircraft depends, as always, on range and payload combinations. The HNZ-57 team estimated that the best DOC scenario would allow the HNZ57 to operate at 18 cents per ton-nmi.

An interesting trade was done to estimate the impact of advanced composite materials on weight and DOC. While manufacturing costs increase when composites are used, the weight savings will reduce DOC. However, above 400,000 lb. of cargo, and for longer missions, composite material expense will pay for itself by reducing fuel costs, even though manufacturing costs are increased. As a result, DOC is reduced by advanced composites.

The Colossus has a 300 foot wing span and a 48 foot high vertical tail (measured from the top of the 23 foot high fuselage. The high wing makes loading and unloading easy.

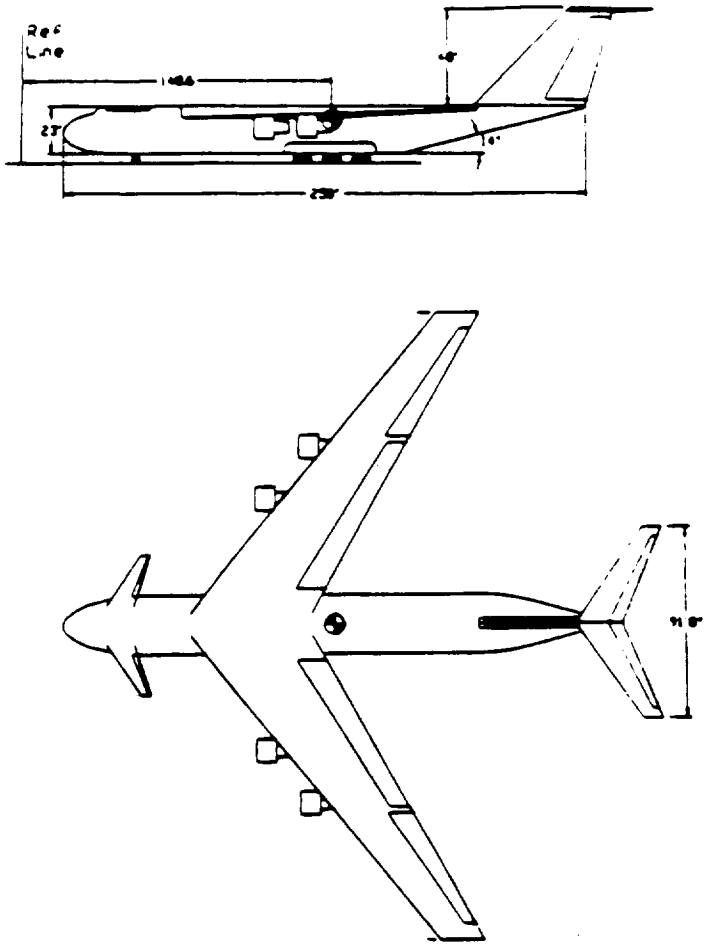

Figure 7 - HNZ57 - Colossus

The VLFP-1 Piggly Wiggly

While we are always concerned with practicality we decided to adopt as our class motto "If it has been done before, don't do it." Nowhere was the motto more visible than on the VLFP-1, shown in Figure 8.

The VLFP-1 is a wing-in-ground-effect machine, or WIG that operates with a power-augmented-ram effect (PAR). It has a payload of 1,200,000 lb. and a predicted range of 8000 nmi. Unlike the other designs which emphasize speed as a means of getting productivity, this aircraft has a maximum speed of only 270 knots at a cruise altitude of 30 feet, giving it a mission flight time of 27 hours.

This aircraft has its origins in Russian ground effect machines in the 1970's (The so-called Caspian Sea monster and the Ekranoplane[16]). It attempts to go head to head with ship cargo by operating from the same seaports. It has unusual constraints and it is different enough from commercial aircraft in use today that some elements of its design are very hard to analyze.

By operating in the ground effect, the drag is reduced considerably,[17] but the span must be large (of the order of 300 feet) to keep away from water spray. Using spanloader weight estimates, the empty weight of this design is only 500,000 lb. On the other hand, it should operate for less than 20 cents per ton-nmi. and deliver cargo in one-tenth the time of ship cargo carriers.

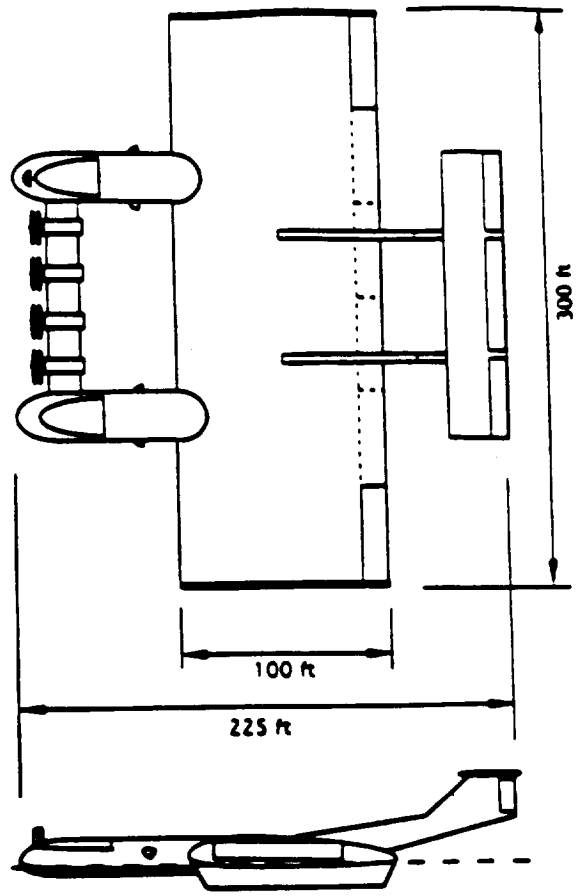

Figure 8 - The VLFP-1, Piggly Wiggly

Conclusions and Recommendations

Purdue design classes considered the engineering and economic tasks of designing a very large cargo aircraft with payloads up to 1,200,000 lb. and a range up to 8000 nmi. These aircraft were powered by a variety of turbojet and turboprop engines. No unconventional propulsion schemes were considered, although the WIG has the size to consider such fuels as hydrogen.

Due to the emphasis placed upon doing things differently, many airplanes were unconventional designs. The use of supercritical airfoils and composite materials was considered as methods of reducing weight. The result was decreased acquisition cost and operating costs.

As aircraft size grows, the effects of the square-cube law on the structure demands a fresh look at advanced, integrated configurations. Most teams accomplished this task, but to differing degrees.

In addition, reduced weight from advanced technology, even though risky from a maintenance standpoint, requires a look at concepts such as fly-by-wire and more advanced composite materials in the primary structure.

All designs had difficulty reducing the cost per ton-nmi. without sacrificing some element of convenience. The aircraft will cost a great deal and this will be reflected in the DOC's. The number of cargo aircraft required in the world is so relatively small compared to commercial airliners. As a result, the construction of a dedicated cargo aircraft of any size is a risky venture, even though the cargo aircraft has a much different mission than the passenger aircraft.

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